Comparison Studies of Candidate Nutrient Delivery Systems for Plant Cultivation in Space

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ABSTRACT

A reliable nutrient delivery system is essential for long-term cultivation of plants in space. At the Kennedy Space Center, a series of ground-based tests are being conducted to compare candidate plant nutrient delivery systems for space. To date, our major focus has concentrated on the Porous Tube Plant Nutrient Delivery System, the ASTROCULTURE™ System, and a zeoponic plant growth substrate. The merits of each system are based upon the performance of wheat supported over complete growth cycles. To varying degrees, each system supported wheat biomass production and showed distinct patterns for plant nutrient uptake and water use.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is conducting studies on procedures for growing plants for gravitational research as well as for bioregenerative life support for humans during long-term space missions. Unique growing procedures are needed to effectively cultivate plants in space (Kliss et al., 1994). A significant challenge is the development of a nutrient delivery system for plants grown in space (Dreschel and Sager, 1989; Kliss et al., 1994; Podolsky and Mashinsky, 1994; Wright, 1984a; Wright, 1984b). Fluids behave differently in microgravity than at 1-g (Haynes, 1979; Podolsky and Mashinsky, 1994). Therefore, many plant nutrient delivery systems used on earth will not function effectively in space (Podolsky and Mashinsky, 1994; Morrow et al., 1994; Morrow et al., 1995). An effective plant nutrient delivery system for spaceflight must provide adequate amounts and uniform distribution of water, nutrient, and oxygen levels in the root zone, while at the same time, prevent release of free nutrient solution to the atmosphere (Kliss et al., 1994).

Solid media such as foam (Levine and Krikorian, 1992), vermiculite mixtures (Lyon, 1968; Brown and Chapman, 1984), and various gelling agents (Mashinsky et al., 1994) that contain predetermined amounts of water and nutrients have been successfully used in passive plant nutrient delivery systems for brief stays in orbit. However, for extended plant cultivation in space, root-zone media will require more than just an initial loading of water and nutrients due to losses from plant evapo-transpiration and nutrient uptake (Salisbury et al., 1994). The ultimate goal is to design a nutrient delivery system that is capable of sustaining plants for long periods under hypogravity, yet require minimal system maintenance and limited demands on crew time (Wright, 1984b; Kliss et al., 1994).

Recent plant testing for spaceflight has begun to explore active nutrient delivery concepts in which water and nutrients are replenished on a continuous basis for long-term plant growth (Morrow et al., 1994; Morrow et al., 1995; Salisbury et al., 1995). Two such concepts currently being tested at KSC employ porous tubes, e.g. Porous Tube Plant Nutrient Delivery System (PTPNDS, developed at the Kennedy Space Center; Dreschel et al., 1994) and the ASTROCULTURE™ Fluid Nutrient Delivery System (developed at the Wisconsin Center for Space Automation and Robotics, WCSAR; Morrow et al., 1994). Within the framework of the ASTROCULTURE™ system, a third concept currently being tested at KSC utilizes a synthetic nutrient zeoponic solid substrate specifically designed to support long-term plant growth in space (developed at the JSC; Ming et al., 1993). Each nutrient delivery concept is described more fully below.

POROUS TUBE PLANT NUTRIENT DELIVERY SYSTEM (PTPNDS)

In the PTPNDS, nutrient solution is constantly circulated under a slightly negative hydrostatic pressure (or suction) through the central cavities of hydrophilic, microporous, ceramic filter tubes (Dreschel et al., 1994).

The slight suction on the nutrient solution prevents excess nutrient solution from collecting on the outer surface of the tube. Seeds are germinated directly on the outer surface of the tube and emerging roots wrap around the outer surface of the tube. Nutrient solution moves through the porous wall of the tube into the rooting environment by capillary attraction (Wright, 1984b; Dreschel and Sager, 1989). Hence, the porous tube serves as a capillary interface between the atmosphere and the nutrient solution. In this scheme, water and nutrient supplies are not buffered by a solid rooting medium and total recovery of root biomass is possible, similar to a hydroponic solution culture. However, the PTPNDS, like conventional hydroponic plant culture, has little buffering capacity, and requires management of nutrient and pH levels to maintain optimal conditions (Dreschel and Sager, 1989).

ASTROCULTURE™

In the ASTROCULTURE™ system, similar to the PTPNDS, water under a slightly negative hydrostatic pressure is delivered to the root zone via porous tubes. However, the porous tubes are fully covered with a high cation exchange capacity (CEC) solid medium such as arcillite (calcined montmorillonite clay) (Brown et al., 1996) or manufactured zeolite (Morrow et al., 1995). The sub-irrigated solid growing matrix provides root anchorage and a buffered source of nutrients. The solid medium acts as a wick to transport nutrients and water to the roots (Cao and Tibbitts, 1996; Morrow et al., 1994). By carefully controlling the pressure on the irrigation lines, the water potential in the medium can be managed at a constant level (Cao and Tibbitts, 1996; Morrow et al., 1994). In our nutrient delivery experiments, we did not employ the full features of the ASTROCULTURE system, such as the condensation of humidity on a cold fritted surface that is captured, and recycled back to the plant watering system (Morrow et al., 1995).

ZEOPONICS

The external medium used with the ASTROCULTURE™ system was a synthetic plant-growth substrate (zeoponic substrate) which was maintained in direct contact with the ASTROCULTURE™ porous tubes. Zeolites are crystalline, hydrated aluminosilicates that contain exchangeable cations within their infinite three-dimensional crystal structures (Ming, 1989). Zeoponic substrate consists of two nutrient charged mineral phases (natural clinoptilolite and either synthetic or natural apatite) designed to release nutrients into solution via dissolution exchange reactions of the clinoptilolite and apatite (Ming et al., 1993; Allen et al., 1995a). Zeoponic substrates are being developed to supply all essential macro- and micronutrients (e.g. slow-release fertilization) to plants over several growth cycles. Hence, plant cultivation in nutrient delivery systems employing zeoponic material would require only the addition of water (Ming et al., 1993).

OBJECTIVES

This paper details our on-going efforts at the Kennedy Space Center to compare the performance of each nutrient delivery concept based largely upon the response of wheat (*Triticum aestivum* L. cv. 'USU-Super Dwarf') during full seed-to-seed life cycles. In a series of ground-based investigations, our primary focus is to characterize the porous tube systems and zeoponic substrate in terms of overall plant growth, nutrient uptake patterns, and water use. Each candidate nutrient delivery systems is contrasted to observations of wheat cultured in solid beds of either zeoponic substrate or peat-vermiculite coupled with conventional surface drip-irrigated nutrient delivery systems.

MATERIALS AND METHODS

The study was carried out in two 1.8 m X 2.4 m walk-in growth chambers (EGC Inc., Chagrin Falls, OH), with each chamber housing two separate nutrient delivery systems replicated 3 times. One chamber housed nutrient delivery systems using standard surface drip-irrigation over either a solid bed of peat-vermiculite or zeoponic substrate. The other chamber housed the two types of porous tube systems, ASTROCULTURE™ (containing zeoponic substrate) and the PTPNDS. All nutrient delivery systems used similar (17 cm wide X 30 cm long) plant trays to hold either zeoponic substrate, peat-vermiculite (contents: perlite, vermiculite, sphagnum peat moss; Metro-Mix 220, Scotts-Sierra Horticultural Products Co., Marysville, OH), or with the PTPNDS, ceramic porous filter tubes (Ceraflo®, U.S. Filter Corporation, Warrendale, PA). The PTPNDS tray housed an array of 5 parallel, 33 cm-long, hydrophilic porous ceramic tubes (0.45 µm nominal pore diameter, OD 2.3 cm, ID 2.1 cm, 2 mm flow channel diameter). The ASTROCULTURE™ plant tray housed an array of 6 parallel, slightly hydrophobic stainless-steel tubes (nominal pore size 30 µm, OD 0.953 cm, ID 0.635 cm, length 30 cm) positioned 1 cm above the tray bottom. The ASTROCULTURE™ stainless-steel porous tubes were evenly covered with a 4 cm layer of zeoponic substrate. The porous tubes in the PTPNDS and ASTROCULTURE™ systems were spaced equidistant 30 mm apart on center. In results presented in this paper, the zeoponics substrate was the first generation material with potassium- and ammonium-saturated Wyoming clinoptilolite, and synthetic apatite (Doug Ming, NASA-JSC, personal communication). The zeoponics particle size was approximately 0.5 - 1.0 mm.

All plant trays (except with the PTPNDS) were filled with solid media to a final depth of 5 cm to give a root media volume of 2.5 L. All nutrient delivery systems were overlaid with an opaque polyethylene plastic cover sheet (white outer surface and black inner surface) to exclude light, prevent algae growth, and maintain high humidity in the root zone. For the ASTROCULTURE™ and drip-irrigated systems, slots were made in the cover sheet of each tray for seed planting and seedling emergence. For the PTPNDS, the parallel edges of the polyethylene cover came together on the upper surface of the ceramic tube to form a slot into which seeds were

planted and through which the seedling shoots emerged (Dreschel et al., 1994). In each nutrient delivery system, wheat seeds were sown in a pattern of 5 rows containing 9 plants per row (or per tube in the PTPNDS) to provide 45 plants per tray. This planting configuration resulted in an effective planting area coverage of approximately 0.05 m^2 per tray (planting density of 900 plants•m^{-2}) in each nutrient delivery system.

Nutrient solution was provided to the root zone environment of each tray and recirculated back to each reservoir using peristaltic pumps. The surface drip-irrigation systems were activated 4 times daily, watering to excess with approximately 700 mL of nutrient solution. The tray for the drip-irrigation systems contained perforated bottoms and were elevated 3 cm to allow passive (gravity) drain flow of excess nutrient solution leachate back to the reservoirs. In a parallel configuration, the tubes in each tray of the PTPNDS and ASTROCULTURE™ systems were supplied a constant flow (approximately 4 - 5 mL•min^{-1}) of nutrient solution via an adjustable stand-pipe siphon connected to a peristaltic pump plumbed to the reservoir. The suction (-0.23 kPa) on the porous tubes was induced by adjusting the standpipe siphon such that a constant hydrostatic head was maintained approximately 2.3 cm below the center line height of the porous tubes. The flow rate through each porous tube was controlled by valve adjustable, panel mounted 65-cm flowmeters in a parallel inlet/common exhaust configuration.

Nutrient solution pH and electrical conductivity (EC) were measured daily from each reservoir with portable hand-held meters. For the PTPNDS and drip-irrigated peat-vermiculite systems, starting at 9 days after planting, nutrient solution (electrical conductivity) EC was maintained at approximately 1200 μS•cm^{-1} by adding a modified concentrated Hoagland's (Hoagland and Arnon, 1950) stock solution to the reservoirs. Deionized water was added daily to all reservoirs to replenish water transpired by the plants. Nutrient solution pH was not controlled. Throughout the study, canopy level photosynthetic photon flux (PPF) levels were monitored and controlled at 350 μmol•m^{-2}•s^{-1} (20 hours light/4 hours dark), relative humidity at 65% ($\pm$ 5%), and CO_2 levels at 1200 μmol•mol^{-1}. All plants were harvested at 77 days. Media samples were taken prior to and after the growth cycle and sent to the University of Florida Soil Testing Lab where extractable soil macronutrient values were determined.

RESULTS AND DISCUSSION

In the PTPNDS and drip-irrigated peat vermiculite systems, solution pH tended to increase (Figure 1) during periods of rapid growth, which corresponds with heavy nitrate (NO_3)-nitrogen uptake (Marschner, 1995). Since only NO_3-nitrogen was used in the modified concentrated Hoagland's stock nutrient solution, this observation was most likely a result of plant charge balance via net HCO_3^- ion efflux from roots (Marschner, 1995). Conversely, pH decreased during

these same periods in the ASTROCULTURE™ and drip-irrigated zeoponics systems, probably as a result of an abundance of nitrogen in the ammonium (NH_4) form in the zeoponic substrate (Allen et al., 1995b). Although initially there was very little extractable NO_3 in the zeoponic substrate, post-growth cycle analysis clearly indicated there was substantial increase in NO_3-nitrogen levels over time (Table 1). Since we did not add an active inoculum of nitrification bacteria, this suggests there was nitrification activity in the zeoponics during the growth cycle. The peat-vermiculite used in our laboratory was spiked with NO_3-nitrogen by the manufacturer (personal communication, Scotts-Sierra Horticultural Products Co.) before packaging and sale. Compared to peat-vermiculite, the zeoponics substrate was very high and well-buffered in available phosphorus, potassium, and calcium (Table 1).
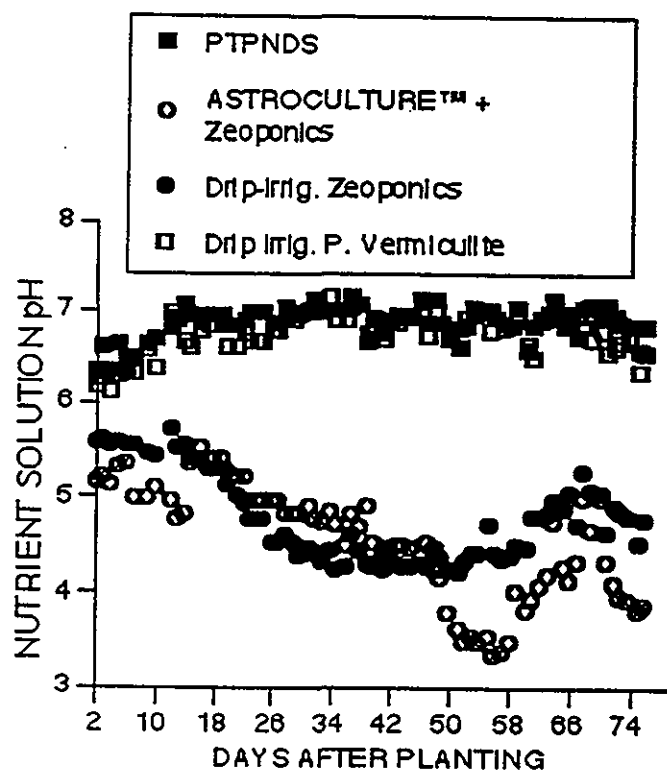

Figure 1. Daily nutrient solution pH values.

Table 1. Extractable nutrient value from solid media sources prior to and following wheat growth experiment.[1]

	Zeoponics			P. Vermiculite	
	Pre-	Astroculture™ Post-	Drip-Irrig. Post-	Pre-	Post-
pH	5.9	6.0	5.7	5.8	6.6
Electrical conductivity	1500	1100	1200	2700	1000
			------mg/L------		
NO_3-N	3.3	26.0	44.5	108.0	1.0
P	30.0+[2]	30.0+	30.0+	6.8	5.2
K	100.0+	65.1	92.2	83.2	100+
Ca	22.4	35.4	41.4	389.0	57.3
Mg	16.2	4.1	8.1	100.0+	43.1

[1]University of Florida, Extension Soil Testing Laboratory, Gainsville, Florida.
[2]Extractable test values noted with a "+" exceeded the highest instrument calibration standard.

However, around 25 days after planting, wheat leaves in the ASTROCULTURE™ and drip-irrigated zeoponics systems showed magnesium deficiency symptoms, i.e. interveinal yellowing on the older leaves (Marschner, 1995). This observation was corroborated by the data which showed (unlike in peat-vermiculite) there was a large reduction of available magnesium in the zeoponic substrates, when comparing media samples before and after the growth cycle (Table 1).

During the first 9 days after planting, the EC of the nutrient solution from all of the nutrient delivery systems declined rapidly (Figure 2), which was indicative of rapid nutrient uptake, especially in a less buffered system such as the PTPNDS. Th change in the pH of the reservoir nutrient solution from the porous tube systems as a reflection of plant growth indicated that there was two-way flow of ions and water involving roots and nutrient solution inside the tube. However, the lack of buffering, like in traditional hydroponic systems, allowed close study of nutrient uptake dynamics. The EC of the zeoponic nutrient solution in the drip-irrigated system rebounded to some extent, and the EC of this particular system stayed relatively constant at approximately 850 μS•cm^{-1} for most of the remainder of the growth cycle. Thus, in a drip-irrigated configuration, the zeoponic nutrient solution had good EC stability. Conversely, in ASTROCULTURE™, the zeoponic nutrient solution EC showed a greater decline over the majority of the growth cycle, when compared to nutrient solution from the drip-irrigated zeoponic system. Starting at 70 DAP, our laboratory experienced a deionized water purification system failure which caused the EC to rise in all of the systems.
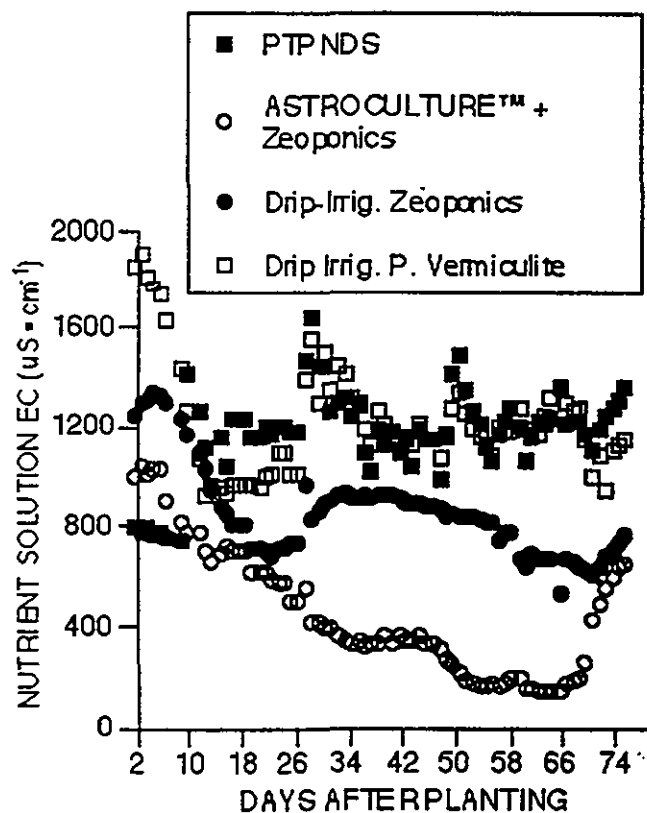

Figure 2. Daily nutrient solution EC values.

The trend for water use in each system reflected a typical water use demand cycle for plant growth (Figure 3). The drip-irrigated systems consumed considerably more water than the porous tube systems. This may be attributed to greater plant water use (as indicated by greater wheat growth in the drip-irrigated systems, Table 2) and unrestrained water evaporation from the drip-irrigation tubing and solid media surfaces. Plants in the drip-irrigated systems were watered to excess, hence satisfying all plant water requirements. On the other hand, plants in the porous tube systems received water chiefly through capillary forces. In this system, plants may have been under water-stress, especially during

4

periods of rapid plant growth. The capacity of the PTPNDS to conserve water has been observed previously (Dreschel and Sager, 1989; Dreschel et al., 1992; Dreschel et al., 1994). Resistance to flow thorough the microporous ceramic tube and accumulations of inorganic and organic substances at the root/tube interface have been suggested as factors that limit water absorption in porous tube systems (Berry et al., 1992).
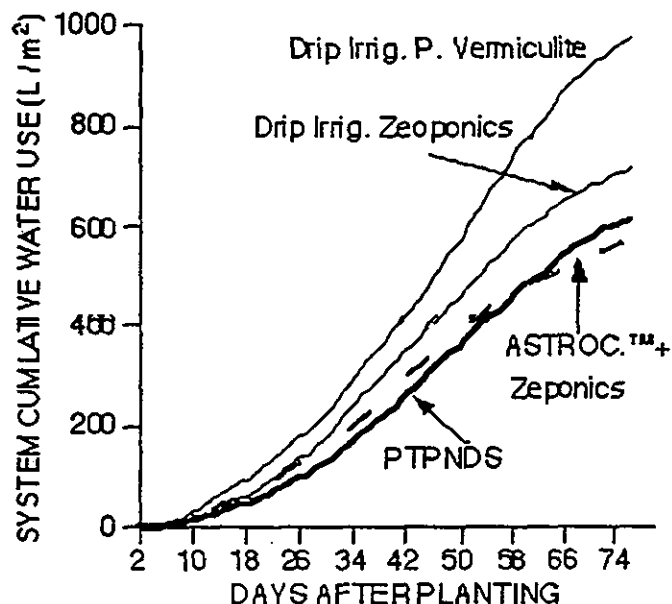

Figure 3. Nutrient delivery system cumulative water use.

Several growth trials by other researchers have indicated that the amount of negative pressure and the pore size of the ceramic tube have significant effects on plant growth (Berry et al., 1992; Dreschel and Sager, 1989; Wright, 1984a). The importance of the physical difference of the root/nutrient solution interface in the PTPNDS versus the root/nutrient solution interface of

solid media or traditional hydroponic systems is unknown (Berry et al., 1992). In the PTPNDS, only one side of each root is in direct contact with the tube surface, while in solid media systems and hydroponics more of the root surface contacts the nutrient solution (Berry et al., 1992). Moreover, root proliferation could have been space limited in the PTPNDS. Restricted rooting volume can limit overall plant growth (Peterson et al., 1984; Ruff et al., 1987). In the PTPNDS, the entire outer surface of the porous tubes was covered by a root matte indicating that all available surface area was utilized. However, the ability to easily recover entire root systems produced on the PTPNDS without cleansing requirements is a significant advantage over solid media nutrient delivery systems.

In terms of aboveground biomass production, seed yield, and harvest index, the drip-irrigated peat vermiculite system was the most successful among the compared nutrient delivery systems (Table 2). The systems using zeoponic substrate produced wheat with excessive seedless tiller formation as compared to wheat produced with the PTPNDS or drip-irrigated peat-vermiculite. Plants in the ASTROCULTURE™ and drip-irrigated zeoponics systems displayed as many as 8 tillers which failed to produce seed. The plants grown in zeoponic substrate were exposed to a mixed-nitrogen source (NH_4 and NO_3), which may have promoted greater tiller formation in those plants. Conversely, wheat grown in the PTPNDS and drip-irrigated peat vermiculite systems were supplied with NO_3-N alone, and these plants produced a maximum of 2-3 tillers per plant. When supplied a mixed-nitrogen source (NH_4 + NO_3) or elevated levels of NH_4 nitrogen, wheat has been shown to have greater vegetative growth due to enhanced development of coleoptilar and higher-order tillers (Camberato and Bock, 1990; Wang and Below, 1992). However, it is important to note that the particular wheat growth cycle reported here was accomplished with the first generation of zeoponic substrate.

Table 2. Wheat harvest data summary ± SE (per tray)[1]

	PTPNDS	Astroculture™ +Zeoponics	Drip-Irrig. Zeoponics	Drip-Irrig. P. Vermiculite
Aboveground DM (g)[2]	96.9 ± 3.5	90.9 ± 0.6	126.8 ± 5.0	148.9 ± 0.6
Straw DM (g)	33.7 ± 2.0	48.1 ± 0.1	78.8 ± 2.0	61.0 ± 0.3
Spike DM (g)	63.2 ± 1.7	44.7 ± 0.5	59.2 ± 3.2	98.9 ± 0.6
Chaff DM (g)[3]	23.0 ± 1.2	35.3 ± 1.1	46.2 ± 1.3	31.6 ± 0.3
Roots (g)[4]	16.5 ± 2	–	–	–
Seed DM (g)	40.3 ± 0.9	8.5 ± 1.5	13.1 ± 1.9	67.2 ± 0.7
Spike No.	104 ± 6	218 ± 6	247 ± 6	155 ± 1
Seed No.	1,422 ± 42	332 ± 73	425 ± 62	2,177 ± 37
Harvest Index (%)[5]	41.5	9.4	10.3	45.1

[1]Means from 45 plants per tray which was equivalent to approximately 900 plants per m^2.
[2]Aboveground dry matter (DM) = Spike DM + Straw DM
[3]Chaff DM = Spike DM - Seed DM
[4]Dashed line indicated roots were not harvested
[5]Harvest index does not include roots

SUMMARY

To varying degrees, each nutrient delivery system in these comparisons supported wheat edible biomass production. During the wheat growth cycle, major differences were observed among the candidate nutrient delivery systems in terms of nutrient solution pH change, plant nutrient uptake, and plant water use. Nutrient delivery system comparison tests at KSC are continuing using refinements of each system.

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